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FINAL REPORT

RSRM 10% SCALE MODEL DRILLED HOLE PLATE TESTS

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PREFACE

This report was prepared by the Huntsville Operation of ERC, Incorporated for the Fluid Dynamics Division of the Science and Engineering Directorate, George C. Marshall Space Flight Center, National Aeronautics and Space Administration. This effort was performed under Contract NAS8-40347 with John E. Hengel, ED34, serving as the Contracting Officer's Technical Representative.

The ERC, Incorporated contributors to this report are David C. Purinton, who serves as Performance Data Analyst, and R. Harold Whitesides, who serves as Project Engineer. Model scaling, design, and test planning contributions were also received from Marshall Space Flight Center Fluid Dynamics Division Personnel. The NASA/MSFC Test Engineer was John E. Hengel, ED34.

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1.0 INTRODUCTION

The RSRM 10% Scaled Model under design will make use of drilled hole liners to provide mass addition along the axial length of the model. The model will have two sets of liners in use at a time. The outer most liner is a flow distribution tube, the purpose of which is to help distribute the flow evenly over each model segment. The inner most liner will simulate the propellant burning surface at a burn time of 80 seconds. This liner will replicate as closely as possible the actual geometry of the full scale RSRM at the 80 second burn time. In order to obtain the correct mass flow rate for the burn time selected, it is necessary to determine the porosity of the holes drilled in each liner and the performance of those holes. The pressure drop across the liners directly effects the uniformity of the flow in the axial direction for a given model section. It is desired to have a pressure drop across the liners which is greater than the axial pressure drop in a given section. However, the pressure drop across the liner also has a bearing on the structural soundness of the model. The performance of the model was determined analytically, but there was some uncertainty as to the value of the discharge coefficient used. This uncertainty was the impetus for these drilled hole plate tests. Experimentally obtaining the discharge coefficients for sample plates of the porosity to be used in the model would increase the fidelity of the model design. These tests were developed in order to provide the required information with the least amount of testing time and hardware.

2.0 OBJECTIVES

The primary objective of the RSRM 10% Scale Model Drilled Hole Plate Tests is to experimentally determine the discharge coefficients for holes drilled in a plate with given porosities and hole sizes. This information will then be used to determine the pressure drop across the drilled hole liners for the RSRM 10% Scale Model. Specific test objectives are as listed below:

Objective 1: Obtain pressure drop measurements across the RSRM 10% Scale Model drilled hole test plates.

These tests will measure the pressure drop across three test plates. These measurements will be taken at varying pressure and mass flow rate conditions. The pressure and flow rate ranges used in these tests will be in the same ranges as those which will be used when the RSRM 10% Scale Model will be tested. The data obtained from these tests will be directly applicable to the design of that model and will be used to validate the design of the liners before model fabrication.

Objective 2: Determine the discharge coefficient for holes drilled in three plates. Each plate will have a unique combination of hole size and porosity.

These tests will experimentally determine the discharge coefficients for a set of three different test plates. Each of the plates will have a unique combination of hole size and porosity. These combinations will replicate the hole design characteristics of the liners in the RSRM 10% Scale Model. The plates will be tested at RSRM 10% Scale Model conditions so that the discharge coefficients are directly applicable to the 10% scale model.

Objective 3: Use the experimentally determined discharge coefficients to predict pressure drops across the liners in the RSRM 10% Scale Model.

At the completion of these tests the data will be used to aid in the prediction of the pressure drops across the liners in the RSRM 10% Scale Model. The pressure drop across the liners is calculated analytically and uses an orifice pressure drop calculation. This calculation requires the input of a discharge coefficient which will be obtained experimentally from these tests. This should yield a much more accurate prediction of the pressure drops than using a discharge coefficient from other sources. Accuracy in the pressure drop calculations will help ensure that the air flow in the model is correctly distributed along the axial length of the model. The pressure drops are also used in the calculations of the loads and stresses in the model.

3.0 TEST REQUIREMENTS

The test conditions for these tests were taken directly from the test conditions which will be used in the RSRM 10% Scale Model. The conditions for that model were developed using similarity parameters. The model conditions were chosen such that the Reynolds Number in the model matched that of the full scale RSRM. This matched condition is only true at the downstream corner of the propellant in the aft segment of the RSRM. In addition, the Mach Number in the model matches that of the full scale RSRM at the same location. This yielded an upstream nominal chamber pressure for these tests of 360 psia and a mass flow rate of approximately 1 lbm/sec. The test conditions are shown in Table 1. Test plate number one was also to be run at plus 50% and minus 50% of the nominal pressure and flow rate which was given above. This would provide a Reynolds Number scan around the area of interest and also provide useful information when making off design predictions for the model performance.

Table I. Drilled Hole Liner Flow/Pressure Drop Test Conditions

Test No.	Plate No.	Plate Porosity	Hole Size (in.)	No. of Holes	Inlet Plenum Pressure (psia)	Pressure Drop (psid)	Mass Flow Rate (lbm/sec)
1	1	1.497%	0.0635	104	360.0	17.39	0.9899
2	2	1.491%	0.1200	29	360.0	17.54	0.9899
3	3	0.993%	0.0635	69	360.0	41.10	0.9899
4	1	1.497%	0.0635	104	540.0	26.08	1.4848
5	1	1.497%	0.0635	104	180.0	8.69	0.4949

The porosity of each plate was also set by requirements for the RSRM 10% Scale Model. Test plates numbers 1 and 2 represent the current design for the propellant liner and the flow distribution tube, respectively. The hole size and porosity for plate number 1 match the design for the RSRM 10% Scale Model. The porosity for plate number 2 matches that for the model but the hole size is only representative of that which is in the model. This discrepancy arises because the flow distribution tube in the model is being fabricated from existing hardware from the ASRM/Technology Model. This model had varying hole sizes in each section of the flow distribution tube and thus there is no single hole size for this piece of model hardware. The value of 0.120 is representative of the size of holes in the flow distribution tube. Plate number 3 was designed such that information on the effect of varying porosity could be obtained from these tests.

4.0 TEST APPARATUS DESCRIPTION

The equipment for these tests was comprised of a simplistic test apparatus coupled with an air supply and its controlling hardware. A schematic of the apparatus is shown in Figure 1. The air supply for these tests was contained in an air trailer which was pressurized before a set of runs was performed. The supply trailer was connected to a pressure regulator with a flexible hose. From the regulator the air passed though a pressure relief valve rated at 600 psia and then to the upstream control valve. This was a hand operated throttle valve which was wide open for these tests. From the control valve the air went to a flowmeter which was used to determine the mass flow rate of the air through the model. A flowmeter was used to determine and record the mass flow rate. The static pressure and temperature were also measured with transducers and recorded by the data recording system. From the flowmeter, the air passed into the test section which is described in further detail below. Downstream of the test section was a control valve which allowed the back pressure in the test apparatus to be controlled. The test apparatus then exhausted into an exhaust pipe which was vented to the atmosphere.

The test chamber consisted of two pressure shells bolted together with a sample test plate sandwiched in between. The apparatus was supplied air through a pipe attached to the upstream end of the pressure shell and air was discharged through an exhaust pipe at the opposite end of the shell. The inlet pipe was designed such that the air being fed into the test rig did not impinge directly upon the test sample. Instead, the air was delivered through a series of holes drilled into the side of the inlet pipe which extended into the pressure shell. This closely models the actual set-up in the RSRM 10% Scale Model where the flow is fed into a plenum area upstream of each liner such that there is no direct impingement upon the liner in an area where there are drilled holes.

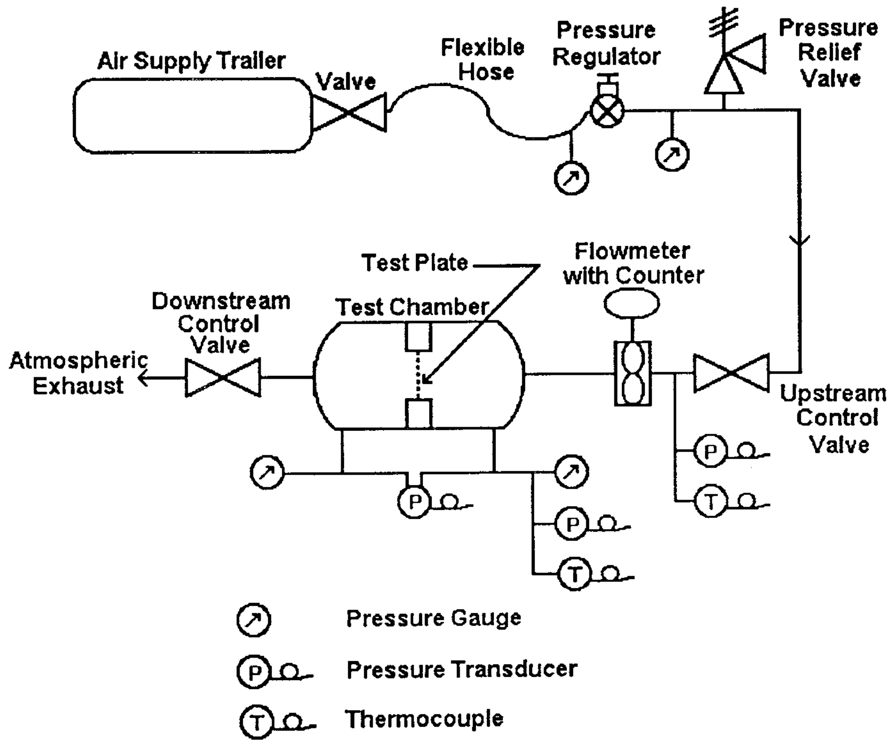


Figure 1. Flow Coefficient Test Apparatus for Drilled Hole Plates

The test samples are held such that each plate has an exposed frontal area of 22.0036 square inches. The porosity calculations for the test plates was based upon this area. This area was multiplied by a porosity and the number of holes for the plate was then determined. Any fractional part of a hole was rounded to the nearest integer value. The test plates were fabricated from the same material and at the same thickness as the liners in the RSRM 10% Scale Model. To increase the fidelity of the experiment and the application of its results to the model the holes were drilled in the same manner as to be used in the fabrication of the model liners. This means the holes were drilled in the same direction of the flow and the holes were deburred as will be done for the model holes. The holes were laid out such that there was a uniform pattern over the plates exposed area. Figures 3, 4, and 5 show the layout of the holes on the three test plates. The pattern for plate number 1 is composed of 104 holes of 0.0635 inches diameter. The holes are laid out in a square pattern with a distance of 0.450 inches between hole centers. This yields a nominal porosity of 1.5% for plate number 1. Plate number 2 in comprised of 29 holes with a diameter of 0.120 inches. The holes in each row are separated by 0.871 inches and each row has a vertical separation of 0.871 inches. There is one odd hole in the pattern which is placed in the center of the plate. The nominal porosity for this plate is 1.5%. The third plate has holes of 0.0635 inches in diameter laid out in a square pattern. The holes are placed 0.550 inches from center to center. The plate has 69 holes which yields a nominal porosity of 1.0%. All three plates have a thickness of 0.250 inches.

5.0 INSTRUMENTATION

The drilled hole tests will have 7 model measurements, which are located at key locations in the facility and test apparatus. These measurements include static pressures, mass flow rate, as well as bulk temperatures. The limited instrumentation for these tests was considered adequate for the data which was required from the tests and also made set-up of the apparatus simple and the quick retrieval of results possible.

A static pressure measurement was taken in the upstream plenum of the pressure shell ahead of the test plate. A delta pressure was taken across the two pressure shell plenum locations to measure the pressure drop across the test sample. Measuring a delta pressure in this way yields a more accurate result then subtracting two absolute static pressures on either side of the test plate. The delta pressure was not taken between the upstream plenum and the hole vena contracta. This greatly simplified the instrumentation and plate design. Also, the model prediction program is set-up to use the downstream plenum pressure instead of the vena contracta pressure. A second absolute static pressure measurement was taken at the flowmeter. This value would be used to calculate the mass flow rate through the meter.

Two static temperature measurements were taken. One of these was at the flow meter to be used in the mass flow rate calculation. The other was taken in the pressure shell plenum upstream of the test plate. This measurement was used to calculate the density of the air for the pressure drop calculations.

The final measurement which was taken from the apparatus was a count from the flow meter. This measurement was in Hertz and was converted to a mass flow rate by the data acquisition software. This conversion was performed in a number of steps. A calibration constant (from a linear curve fit of calibration data) for the flow meter was used to convert the counts to a volumetric flow rate as follows:

$$ACFM = 0.040 * (\text{Counts per Seconds}) \quad (\text{cu. ft./min})$$

The mass flow rate through the system was calculated from this volumetric flow rate by using the following equation:

$$\dot{m} = \frac{\rho_m * ACFM}{60} \quad \text{(lbm/sec)}$$

where ρ_m is the density (lbm/cu. ft.) of the air at the flow meter.

6.0 MODEL PERFORMANCE and DATA REDUCTION

The data from the test plates was used to determine the pressure drop across the plates as well as to determine the discharge coefficient of the holes in the test plates. This discharge coefficient is used in a prediction of the pressure drop across the drilled hole liners in the RSRM 10% Scale Model. The pressure drops across the plates was directly measured and thus was taken directly from the test results. The discharge coefficients needed to be calculated from the test results. This was done using the same logic which is used to predict the pressure drops across the liners in the model, with the analysis changed so that the discharge coefficient is the unknown instead of the pressure drop.

The discharge coefficient was determined in the following manner. The inputs to the analysis are the pressure drops across the test plates, the upstream pressure on the plates, the temperature of the air upstream of the test plates, the hole porosity and hole size, and the mass flow rate. These quantities are then used to calculate a discharge coefficient for each run made with each plate. The air density is calculated from the downstream pressure (psia) and temperature (Deg. R) with the following equation:

$$\rho = \frac{P_2 * 144}{R * T_2} \quad \text{(lbm/cu. ft.)}$$

where R (lbf*ft/(lbm*Deg R)) is the ideal gas constant. An upstream approach diameter was calculated by taking the total exposed area of the test plate and dividing it up evenly amongst the holes on the plate. This area per hole was then used to calculate the upstream diameter per hole as follows:

$$D_1 = 2 * \sqrt{\frac{A_1}{n * \pi}} \quad \text{(inches)}$$

where A_1 (sq. in.) is the exposed plate area and n is the number of holes per plate. The flow coefficient is a function of the discharge coefficient and the contraction ratio of the flow.

$$K = \frac{C_D}{\sqrt{1-\left(\frac{D_2}{D_1}\right)^4}}$$

where D_2 (in.) is the drilled hole diameter. The equation for the expansion factor is:

$$Y = \frac{1-\left(0.41+0.35 * \left(\frac{D_2}{D_1}\right)^4\right) * (P_1 - P_2)}{\gamma * P_1}$$

where γ is the ratio of specific heats and has the value of 1.4 for air in this analysis. The calculated value of P_1 is obtained as follows:

$$P_1 = \frac{\left(\dot{m} * 24 * \sqrt{2} \Big/ \left(n * \pi * g_o * K * Y * D_2^2\right)\right)^2}{\rho} + P_2 \qquad \text{(psia)}$$

where g_o is the constant of acceleration and has a value of 32.174 ft/sec^2. The solution is obtained by calculating a value for P_1 and comparing it to the measured value of P_1. The discharge coefficient is then iterated upon until the calculated and the measured values of P_1 match. Microsoft Excel 5.0 was used to iteratively solve for the discharge coefficient.

7.0 EXPERIMENTAL RESULTS

A number of runs were made with each of the three test plates. After some initial problems with the facility, there were approximately thirty runs made from which usable data was obtained. The data was analyzed using the analysis outlined above and discharge coefficients were calculated for each run. The initial results were questionable and the actual sizes of the drilled holes became the leading issue. The holes were measured and the as-fabricated values were then used in the analysis and a new set of discharge coefficients were calculated. The holes which were nominally 0.0635 inches were measured at 0.0620 inches. The holes which were 0.120 inches nominally were measured at 0.119 inches. These new hole sizes resulted in new porosities for each of the three plates. These new porosities were 1.427%, 1.466%, and 0.947% for plates 1, 2, and 3, respectively. The new results were plotted, reviewed, and judged acceptable.

Figure 6 shows the discharge coefficients plotted versus mass flow rate for all three plates. This figure also shows a least squares linear fit for each plate. The variation in the flow rate for each plate gives data on the effect of Reynold's Number on the discharge coefficient. The ratio of the highest flow rate to the lowest flow rate is 3.41, 2.25, and 2.76 for plates 1, 2, and 3, respectively. These ratios correspond to values of 3.03, 2.28, and 2.60 for the ratio of the highest upstream pressure to the lowest upstream pressure for each of the plates tested. Figure 6 shows that the discharge coefficient increases with mass flow rate, and thus the Reynold's Number. The rise is approximately equal for plates 1 and 2 which share approximately the same porosity. Plate 3 has a much steeper rise in discharge coefficient per increase in mass flow rate. This plate has a lower porosity than the other two plates tested. The slopes for the curve fits for plates 1, 2, and 3 are 0.00308, 0.00568, and 0.01741, respectively.

The measured discharge coefficients for the three drilled hole plates tested are approximately fifty percent higher than the generally accepted discharge coefficients for an orifice. The reason for this discrepancy is related to the geometry of the holes in these test plates. The L/D ratio for the holes in plates #1 and #3 is 3.94 and for plate #2 the value is 2.08. These larger L/D ratios allow the flow at the vena contracta to expand in the hole such that the flow has reattached to the sides of the hole before the flow reaches the exit plane of the hole. The pressure recovery gained in this expansion yields the higher than expected discharge coefficients.

The curve fits for plate #1 and #2 were used to determine the discharge coefficient for use in the pressure drop analysis for the flow distribution tube liners as well as the propellant liners for the RSRM 10% Scale Model. This was done by calculating the test sample mass flow rate which matched the model flow rate for mass flow per unit area. This value was then used along with the equation for the curve fit to determine the discharge coefficient to use for the propellant liner as well as the flow distribution tube. The discharge coefficient used for the propellant liner was 0.910 and the discharge coefficient used for the flow distribution tube liner was 0.922. When this was done, it was determined that no changes would need to be made in the liner designs as the pressure drops were still within the required ranges. The nominal pressure drop for the flow distribution tube became 7 psid and the nominal pressure drop for the propellant liner became 15 psid.

8.0 CONCLUSIONS

As a result of these tests a number of conclusions can be drawn. These are as follows:

1. Accurate pressure drop data could be generated by the use of a simplistic test apparatus with limited instrumentation.

2. The discharge coefficients for the three tests plates did differ and were also a function of the mass flow rate through the plates. The discharge coefficient increased with increasing mass flow rate. The rate of increase was greater for the plate with the lower porosity than it was for the two plates with similar porosity.

3. A discharge coefficient of 0.910 was found to best represent the propellant liner hole pattern and a discharge coefficient of 0.922 was the appropriate value for the flow distribution tube liner at the nominal model pressure and flowrate.

4. No changes need to be made in the design of the two liners for the RSRM 10% Scale Model as these test results show that the initial estimate for the pressure drops and the corrected values for the pressure drops are in close enough agreement.

Table II. Drilled Test Plate Pressure Drop Calculations

Test Data

Constants		
	Gas Const: 53.353	Gamma: 1.4
Test Area: 22.0036 sq. inches	Test Dia: 5.293 inches	

Calculations - Test Plate #1

Run No.	Hole Dia.	Temp.	Density	No. of Holes	Area/Hole	D1	Hole Velocity	P2 (input)
***	in.	Deg. R	lbm/cu. ft.	***	sq. in.	in.	ft/sec	psia
29/0	0.0620	505.23	0.873438	104	0.211573	0.5190214	301.01	154.01
18/0	0.0620	487.33	1.076655	104	0.211573	0.5190214	327.31	180.64
28/0	0.0620	505.89	1.120597	104	0.211573	0.5190214	301.55	197.84
35/0	0.0620	482.12	1.18318	104	0.211573	0.5190214	277.52	200.44
34/0	0.0620	482.01	1.450545	104	0.211573	0.5190214	278.82	245.58
27/0	0.0620	506.83	1.434254	104	0.211573	0.5190214	303.09	253.74
33/0	0.0620	481.20	1.730067	104	0.211573	0.5190214	280.30	292.30
16/0	0.0620	490.92	2.015127	104	0.211573	0.5190214	333.45	340.23
16/1	0.0620	489.79	2.002969	104	0.211573	0.5190214	308.99	340.73
30/0	0.0620	486.32	2.005495	104	0.211573	0.5190214	284.29	342.13
32/0	0.0620	480.31	2.235469	104	0.211573	0.5190214	278.55	377.38
17/0	0.0620	493.16	2.710717	104	0.211573	0.5190214	335.66	459.87
31/0	0.0620	486.28	2.811565	104	0.211573	0.5190214	278.96	480.16

Run No.	Porosity	Disch Coeff	Exp. Fact.	Flow Coeff.	Mass Flow	Mdot/A	P1	Delta P
***	percent	***	***	***	lbm/sec	lbm/sec/in^2	psia	psid
29/0	1.427	0.909	0.982999	0.909073	0.54	0.02454	163.500	9.490
18/0	1.427	0.902	0.979267	0.90252	0.714	0.03245	194.400	13.760
28/0	1.427	0.910	0.982987	0.909734	0.694	0.03154	210.040	12.200
35/0	1.427	0.914	0.98488	0.914231	0.679	0.03086	211.350	10.910
34/0	1.427	0.915	0.984769	0.915018	0.836	0.03799	259.050	13.470
27/0	1.427	0.915	0.983045	0.91527	0.893	0.04058	269.330	15.590
33/0	1.427	0.917	0.984664	0.917212	1.002	0.04554	308.450	16.150
16/0	1.427	0.909	0.978983	0.909164	1.36	0.06181	366.530	26.300
16/1	1.427	0.909	0.981667	0.909507	1.265	0.05749	363.480	22.750
30/0	1.427	0.917	0.984413	0.917289	1.177	0.05349	361.360	19.230
32/0	1.427	0.922	0.98495	0.921689	1.288	0.05854	397.820	20.440
17/0	1.427	0.915	0.979048	0.914672	1.842	0.08371	495.300	35.430
31/0	1.427	0.910	0.984735	0.910322	1.621	0.07367	506.560	26.400

Table II. Drilled Test Plate Pressure Drop Calculations
Test Data

Constants		
	Gas Const: 53.353	Gamma: 1.4
Test Area: 22.0036 sq. inches	Test Dia: 5.293 inches	

Calculations - Test Plate #2

Run No.	Hole Dia.	Temp.	Density	No. of Holes	Area/Hole	D1	Hole Velocity	P2 (input)
***	in.	Deg. R	lbm/cu. ft.	***	sq. in.	in.	ft/sec	psia
14/2	0.1190	477.68	1.976848	29	0.758745	0.9828854	416.32	313.16
14/3	0.1190	481.79	1.876234	29	0.758745	0.9828854	416.68	299.90
15/0	0.1190	470.42	2.446099	29	0.758745	0.9828854	399.88	384.13
13/1	0.1190	462.77	1.09192	29	0.758745	0.9828854	398.37	168.33

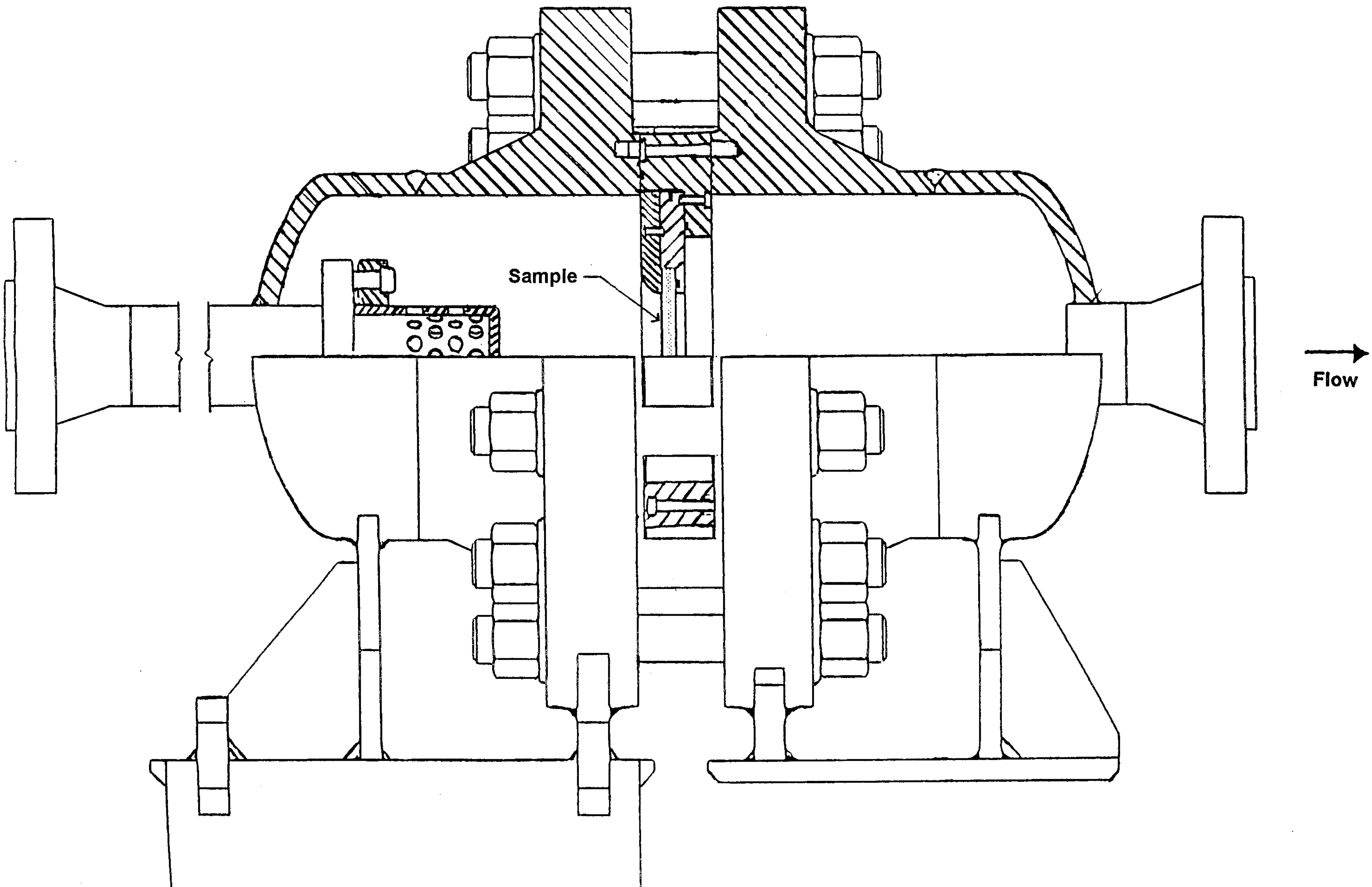
Run No.	Porosity	Disch Coeff	Exp. Fact.	Flow Coeff.	Mass Flow	Mdot/A	P1	Delta P
***	percent	***	***	***	lbm/sec	lbm/sec/in^2	psia	psid
14/2	1.466	0.927	0.969266	0.926817	1.65	0.07499	349.870	36.710
14/3	1.466	0.925	0.969373	0.92552	1.568	0.07126	334.920	35.020
15/0	1.466	0.928	0.971	0.92793	1.974	0.08971	426.340	42.210
13/1	1.466	0.922	0.970446	0.921836	0.876	0.03981	187.220	18.890

Calculations - Test Plate #3

Run No.	Hole Dia.	Temp.	Density	No. of Holes	Area/Hole	D1	Hole Velocity	P2 (input)
***	in.	Deg. R	lbm/cu. ft.	***	sq. in.	in.	ft/sec	psia
20/0	0.0620	494.15	1.056826	69	0.318893	0.6372023	354.21	179.01
25/0	0.0620	487.18	1.150947	69	0.318893	0.6372023	343.38	192.95
24/0	0.0620	480.06	1.468975	69	0.318893	0.6372023	341.01	242.65
23/0	0.0620	480.80	1.689067	69	0.318893	0.6372023	342.11	279.32
19/0	0.0620	497.04	1.994279	69	0.318893	0.6372023	361.10	339.49
19/1	0.0620	482.11	2.053239	69	0.318893	0.6372023	346.44	340.38
21/0	0.0620	495.26	2.744727	69	0.318893	0.6372023	364.63	465.10

Run No.	Porosity	Disch Coeff	Exp. Fact.	Flow Coeff.	Mass Flow	Mdot/A	P1	Delta P
***	percent	***	***	***	lbm/sec	lbm/sec/in^2	psia	psid
20/0	0.947	0.940	0.978082	0.940304	0.501	0.02277	193.490	14.480
25/0	0.947	0.944	0.979135	0.943594	0.531	0.02413	207.750	14.800
24/0	0.947	0.943	0.979117	0.943536	0.673	0.03059	261.280	18.630
23/0	0.947	0.943	0.979004	0.943019	0.776	0.03527	300.890	21.570
19/0	0.947	0.950	0.977854	0.950305	0.963	0.04377	367.260	27.770
19/1	0.947	0.952	0.978934	0.951885	0.955	0.04340	366.760	26.380
21/0	0.947	0.955	0.977583	0.95479	1.337	0.06076	503.650	38.550

Figure 2. Drilled Hole Plate Tests Pressure Shell



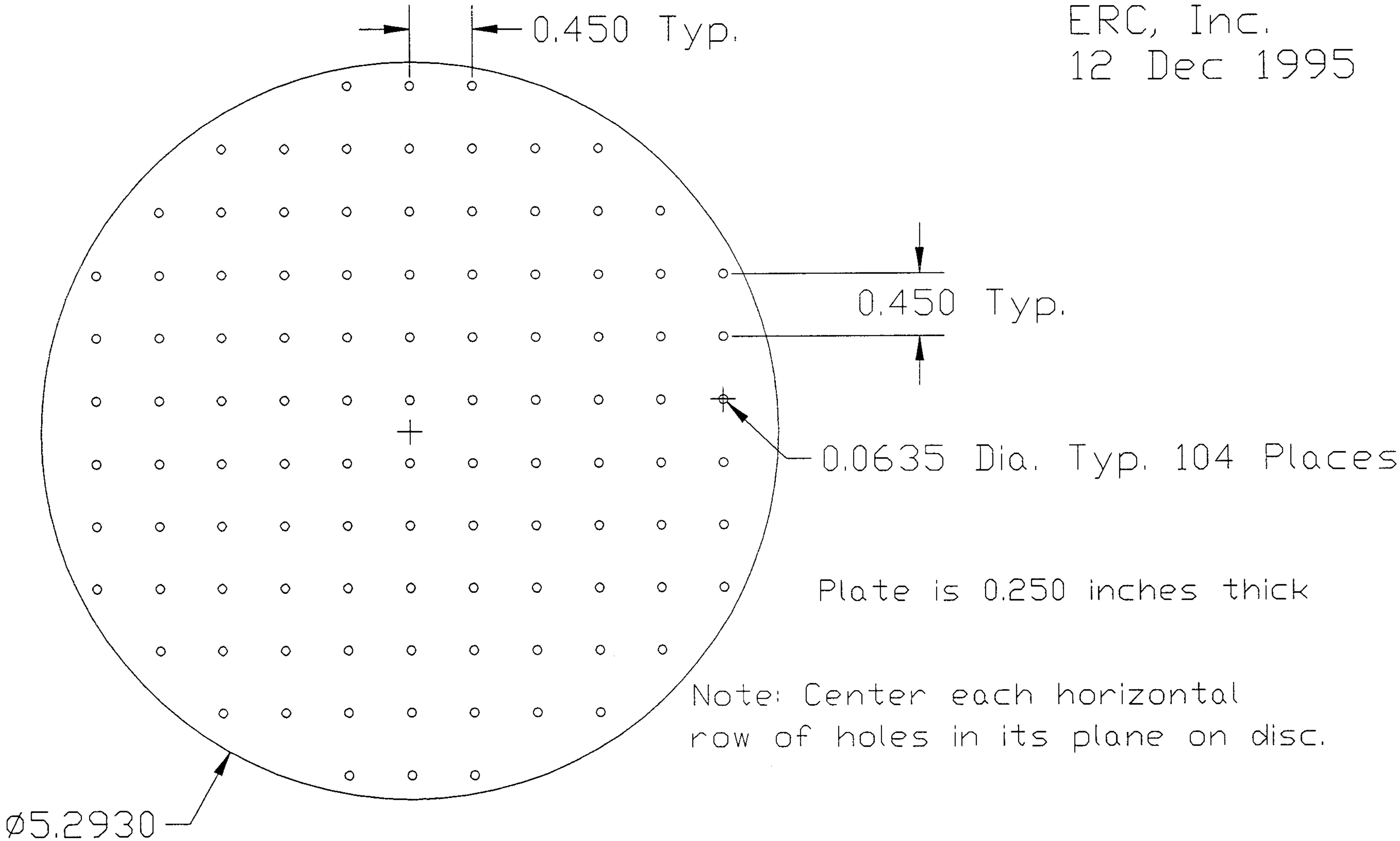


Figure 3. Test Plate No. 1, Porosity=1.5%
Hole Dia.=0.0635 inches

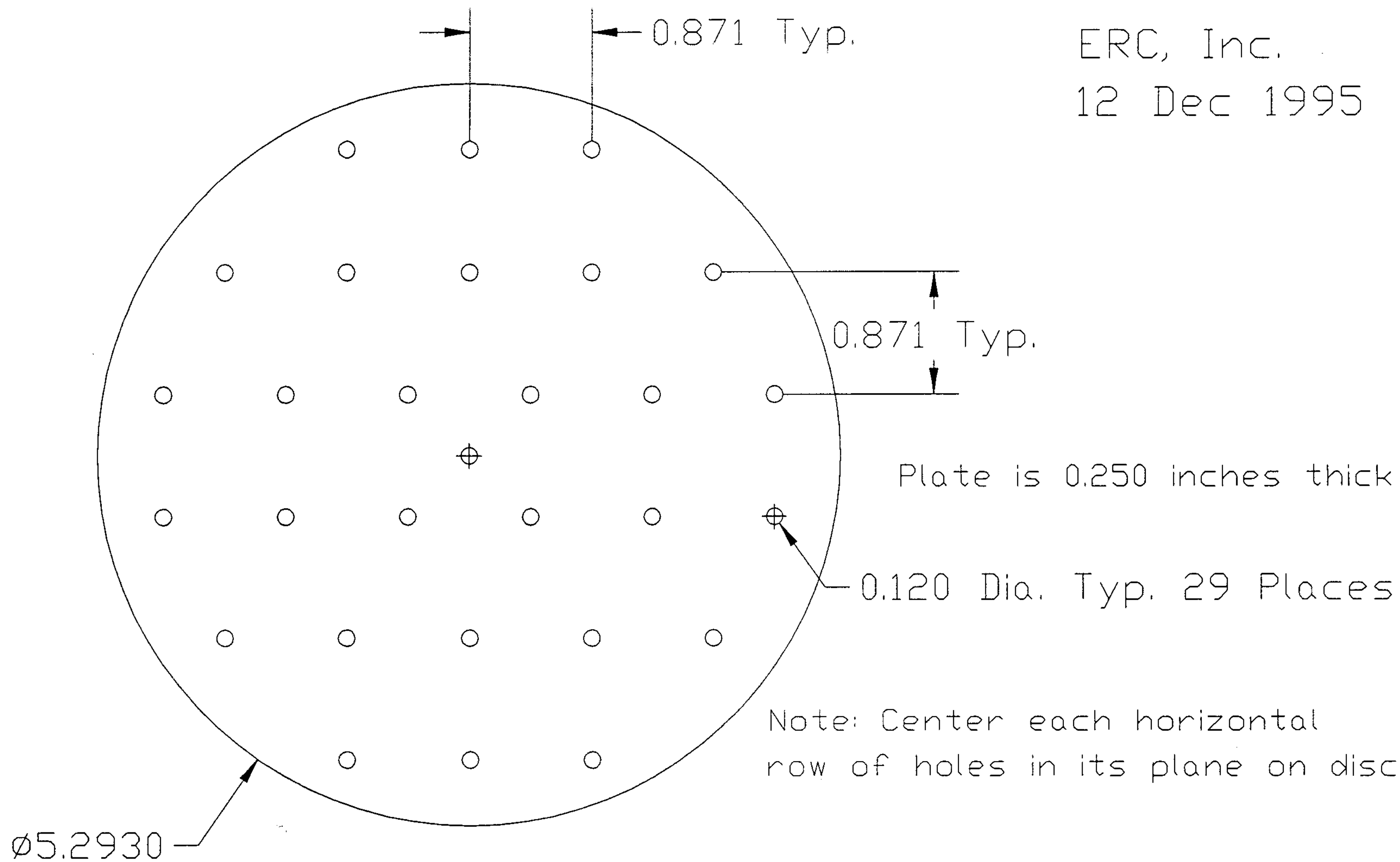


Figure 4. Test Plate No. 2, Porosity=1.5%
Hole Dia.=0.120 inches

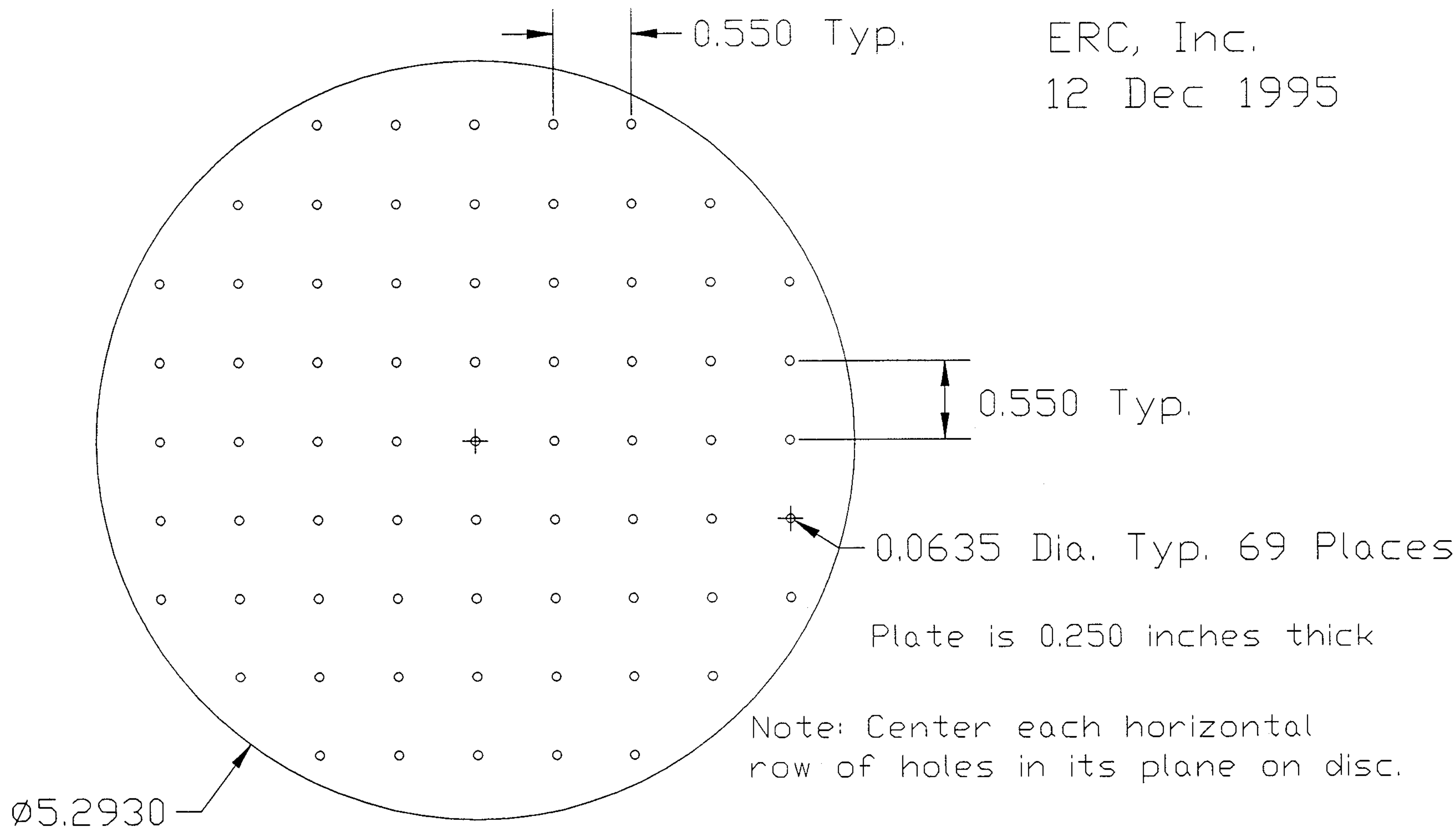
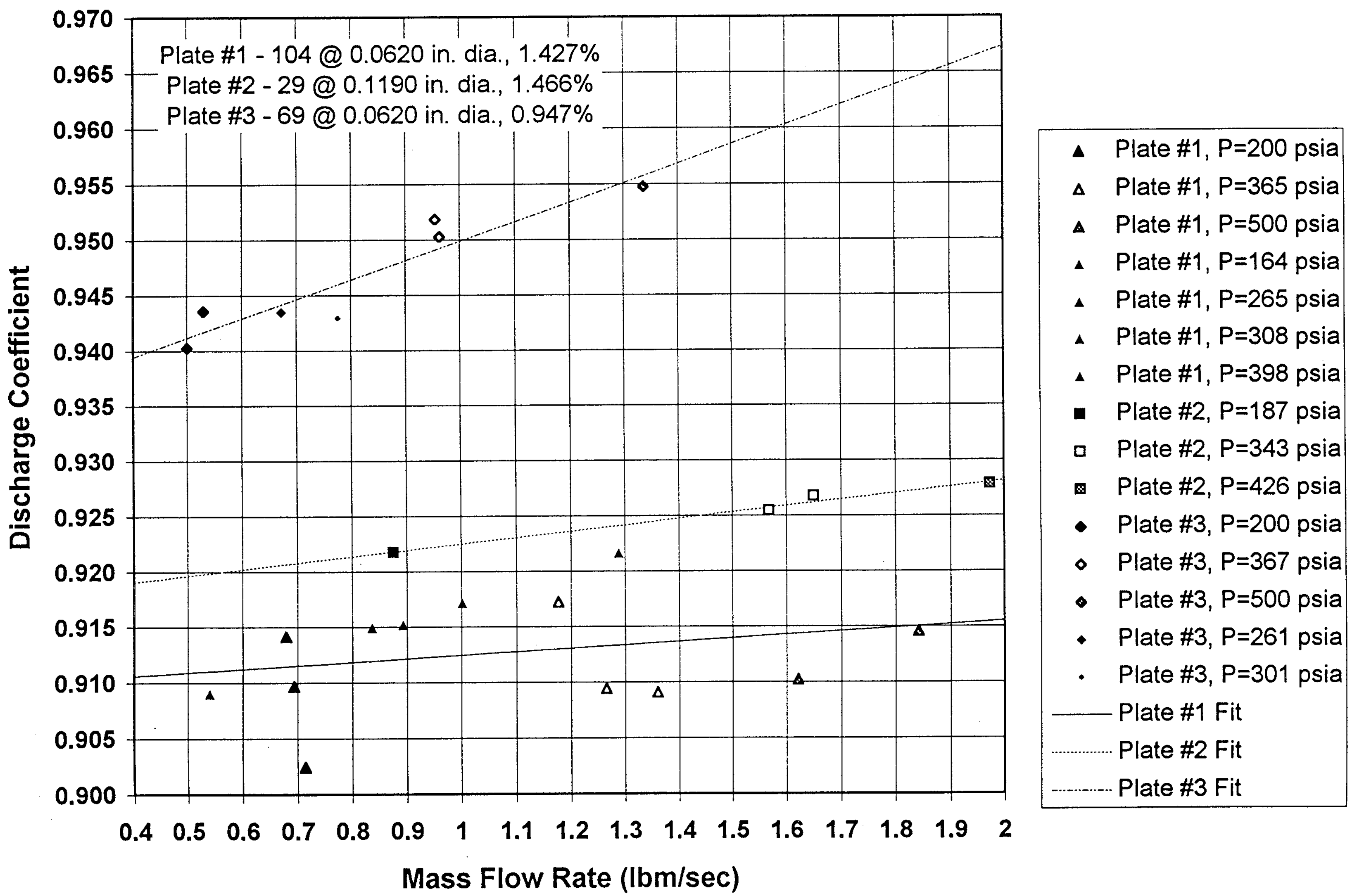


Figure 5. Test Plate No. 3, Porosity=1.0%
Hole Dia.=0.0635 inches

Figure 6. RSRM 10% Scale Model Test Plates



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